Overcoming Barriers to the Adoption of Wide-Bandgap Semiconductors for Power Electronics

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***Abstract*—Wide-bandgap (WBG) power semiconductor devices offer enormous energy efficiency gains in a wide range of potential applications. As silicon semiconductors are fast approaching their performance limits for high power requirements, WBG semiconductors such as gallium nitride and silicon carbide with their superior electrical properties are likely candidates to replace silicon in the near future. Along with higher blocking voltages, WBG semiconductors offer breakthrough relative circuit performance enabling low losses, high switching frequencies, and high temperature operation. However, even with the considerable materials advantages, a number of challenges are preventing widespread adoption of power electronics using WBG semiconductors. The U.S. Department of Energy's Advanced Research Project Agency for Energy (ARPA-E), has launched several programs to fund transformational innovations in WBG semiconductor technology in order to overcome the barriers to adoption in power electronics. From materials and devices to modules and circuits to application-ready systems integration, ARPA-E projects have demonstrated the potential of WBG semiconductors in high-efficiency power electronics to enable broad adoption in energy applications.**

Keywords— Wide-Bandgap Semiconductors, Power Electronics, Silicon Carbide, Gallium Nitride, Circuits, Packaging, Controls

I. Introduction

Electricity generation currently accounts for ~38% of primary energy consumption in the U.S [1] and over the next 25 years is projected to increase more than 50% worldwide [2]. As a result, electricity continues to be the fastest growing form of end-use energy. Power electronics play a significant and growing role in the delivery of electricity as they are utilized to control and convert electrical power to provide optimal conditions for transmission, distribution, and load-side consumption. Estimates suggest that the fraction of electricity processed through some form of power electronics could be as high as 80% by 2030 (including generation and consumption), approximately a twofold increase over the current percentage [3]. Therefore, advances in power electronics have the potential for enormous energy efficiency improvements. A key element of any power electronic system is the semiconductor switching device which determines the frequencies and power levels at which the electronic system may operate.

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A significant portion of the losses in power electronic converters is dissipated in the power semiconductor devices. Silicon (Si) has been the semiconductor material of choice for power devices for quite some time due to cost, ease of processing, and the vast amount of information available about its material properties. Si devices are, however, reaching their operational limits in blocking voltage capability, temperature of operation, and switching frequency due to the intrinsic material properties of Si. Wide-bandgap (WBG) power semiconductors, with their superior electrical properties, are an attractive emerging alternative to Si in many applications and can enable power converters with higher efficiency and higher power conversion densities

II. Benefits of Wide-Bandgap Semiconductors

Achieving high power conversion efficiency requires low-loss power semiconductor switches. Today's incumbent power switches, typically metal oxide field effect transistors (MOSFET), insulated gate bipolar transistors (IGBT) and thyristors, are Si based and are quickly approaching their limits due to the fundamental material properties of Si and have several important limitations:

High Losses: The relatively low bandgap (1.1 eV) and critical electric field (0.3 MV/cm) of Si require high voltage devices to have substantial thickness. The large thickness translates to devices with higher specific on-resistance and results in higher conduction losses.

Low Switching Frequency: Si power MOSFETs require large die areas to keep conduction losses low. As the die size increases the gate capacitance and charge increases resulting in increases in switching losses for high-frequency applications. Si IGBTs have smaller die sizes compared to MOSFETs as they utilize minority carriers for conductivity modulation, but the long lifetime of minority carriers in Si reduces the usable switching frequency range of IGBTs to <10kHz.

Poor High-Temperature Performance: The relatively low Si bandgap contributes to higher intrinsic carrier concentrations at elevated junction temperatures which produces high leakage currents in p-n junctions. Additionally, the temperature variation of the bipolar gain in IGBTs amplifies the leakage and limits the maximum junction temperature to ~150°C. New opportunities for higher efficiency power electronics have emerged with the development of wide-bandgap power semiconductor devices, driven by the fundamental differences in material properties between Si and the WBG semiconductors. Figure 1 illustrates one of the advantages of WBG semiconductors and shows the unipolar limit relationship as a function of on-resistance and breakdown voltage for Si, Silicon Carbide (SiC), and Gallium Nitride (GaN). The lower right region of the plot represents higher performance devices and thus is more desired.

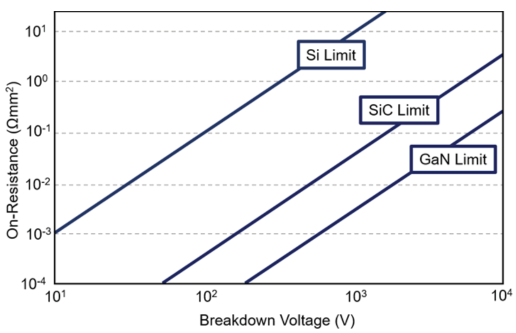

Fig. 1. Semiconductor On-Resistance ($\Omega.mm^2$) versus breakdown voltage for Si, SiC, GaN.

New opportunities for higher efficiency power electronics have emerged with the development of wide-bandgap power semiconductor devices, driven by the fundamental differences in material properties between Si and the WBG semiconductors. Figure 1 illustrates one of the advantages of WBG semiconductors and shows the unipolar limit relationship as a function of on-resistance and breakdown voltage for Si, Silicon Carbide (SiC), and Gallium Nitride (GaN). The lower right region of the plot represents higher performance devices and thus is more desired. Higher critical electric fields in WBG materials (>2 MV/cm) enable thinner, more highly doped voltage-blocking layers, which can reduce on-resistance by an order of magnitude in majority carrier architectures relative to equivalent Si devices [4]. High breakdown electric field and low conduction losses mean that WBG materials can achieve the same blocking voltage and on-resistance with a smaller form factor. This reduced capacitance allows higher frequency operation compared with a Si device. The low intrinsic carrier concentration of WBG materials enables reduced leakage currents and robust high-temperature performance. WBG semiconductors permit devices to operate at much higher temperatures, voltages, and frequencies therefore providing a pathway to more efficient, lighter, smaller, and higher temperature capable power electronics than those made from conventional semiconductor materials.

III. Potential Applications

High impact opportunities exist across a wide variety of potential applications.

Motor Drives: Across all sectors, electric motors account for approximately 40% of total U.S. electricity demand [5]. It is estimated that 40-60% of currently installed electric motors could benefit from variable frequency drives (VFDs) [6], which enable efficient adaptation to speed and torque demands. Depending on the application, incorporation of VFDs can reduce energy consumption by 10-30% [7]. Conventional VFDs are bulky and occupy significant space. Size, power density and efficiency can be improved, and the overall system cost reduced, by using WBG-based VFDs.

Automotive: Power electronics such as traction inverters, DC boost converters, and on-board battery chargers are critical elements in hybrid and electric vehicles (EVs), impacting energy efficiency in two ways: directly through switching and other losses, and indirectly by adding volume and weight. WBG inverters can reduce both direct and indirect losses by operating at higher switching frequencies, efficiencies, and temperatures [8]. As a result, 15% improvement in energy efficiency has been predicted for representative hybrid EVs employing SiC traction inverters, with even larger energy savings possible with increased drivetrain electrification [9]. Assuming aggressive market adoption of EVs in the U.S., use of WBG vehicle power electronics could save as much as 1 quadrillion Btu of energy per year by 2050 relative to conventional Si-based systems [10]. Additionally, efficient, lightweight, and low-cost DC fast charging infrastructure (>120 kW) enabled by WBG converters can advance the commercial viability of EVs, which, in conjunction with a cleaner electricity generation portfolio, has the potential to significantly reduce the one quarter of total U.S. greenhouse gas emissions that stem from the transportation sector [11].

Data Centers: Energy consumption in data centers accounts for approximately 2% of electricity use in the U.S. in 2014 [12]. The power delivery architecture of most modern data centers consists of a line frequency transformer, low voltage power distribution network, centralized backup unit, and inefficient voltage regulators [13]. Strategies to improve energy efficiency range from integration of lower loss power converters to complete redesign of the power delivery network [14].The latter approach often involves converting higher voltages at the rack level, where space is limited and proper thermal management is imperative. Converters based on WBG devices can be key enablers for more efficient systems, as operation at higher temperature can reduce cooling loads and further boost data center grid-to-chip efficiency.

Aerospace: Longer, thinner, and lighter wings can reduce fuel consumption and carbon emissions by 50% relative to current commercial aircraft [15]. Such a reduction would save approximately 1 quadrillion Btu of energy per year across the U.S. fleet at current demand [16]. Achieving this wing design requires electromechanical actuators that are small and lightweight with robust operation over a wide temperature range [17]. Electrification of environmental controls, fuel pumps, brakes, and de-icing systems can further reduce weight and increase efficiency through elimination of bleed air controls and pneumatic/hydraulic systems [18]. WBG-based converters, with high gravimetric and volumetric power density and high temperature operation, offer a pathway to achieving significant energy savings in air transport by reducing weight in electric aircraft and enabling new paradigms in body design.

Distributed Energy Resources: In grid applications, such as solar photovoltaic (PV) and wind, storage integration, as well as the emerging fields of medium voltage direct current (MVDC) distribution, high voltage direct current (HVDC) and flexible alternating current transmission systems (FACTS), power conditioners are required to process and control the flow of electricity by supplying voltages and currents in a form that is optimally suited to the load. Power electronics are responsible for a loss of about 4% of all of the electricity generated in these applications and are the dominant point of failure for installed systems [19]. Novel WBG electronic circuits present a route to lower system-level costs by operating at higher switching frequencies that reduce the size of passive components and lower the overall system footprint. In addition, WBG circuits will increase system-level efficiency by allowing PV arrays to operate at higher voltages (e.g. medium voltage levels), enabling DC systems with fewer voltage conversions replacing traditional combiner boxes with DC/DC converters, eliminating the need for on-site AC transmission lines, and ultimately allowing easier integration of energy storage solutions in the central substation. Together with a higher semiconductor operating temperature, the advantages of WBG electronics offer a pathway to more robust power converters with mean time to failure (MTTF) comparable to the generation system lifetime, which is typically >25 years. This will lower the equipment replacement cost and total plant Operation & Maintenance and have a significant impact on the levelized cost of electricity in distributed resource applications.

IV. Barriers to Adoption

However, even with the considerable materials advantages, a number of challenges are preventing widespread adoption of power electronics using WBG semiconductors

- Cost: The high cost and small size of GaN and SiC substrates lead to higher costs for WBG power devices compared to similarly rated silicon power devices.

- Device Design and Fabrication: Novel device designs are required that effectively exploit the proper-ties of WBG materials to achieve the voltage and current ratings required in certain applications. Alternative packaging materials or designs are also needed to enable higher temperature and higher frequency operation.

- Proven Reliability: Demonstration of WBG device reliability in the field is needed before large scale industrial adoption of WBG based power electronics

- Systems Integration: WBG devices are not always suitable drop-in replacements for Si-based devices. The larger, more complex systems must be redesigned to integrate the WBG devices in ways that deliver unique capabilities.

High cost, challenging fabrication of practical devices, demonstrated reliability, and system integration remain important barriers to the widespread adoption of WBG devices. SiC and GaN substrates are expensive and limited in size, 150 mm and 100 mm, respectively. This is illustrated in Figure 2 which shows WBG substrates have a per area cost an order of magnitude higher compared to a 200 mm Si substrate. This results in higher cost for SiC and GaN power devices compared to similarly rated silicon power devices. In order to take full advantage of the superior properties of the WBG semiconductors devices have to be developed that address key materials, device fabrication, and device architecture issues that impact the cost and reliability of the devices. One such challenge in GaN is the requirement of selective area doping to fabricate normally-off vertical device architectures. The current lack of a viable selective area doping processes in GaN limits the possible devices architectures and ultimately limits the performance of the devices. Additionally advanced device packaging needs to be developed to enable the higher temperature capability of the WBG semiconductors.

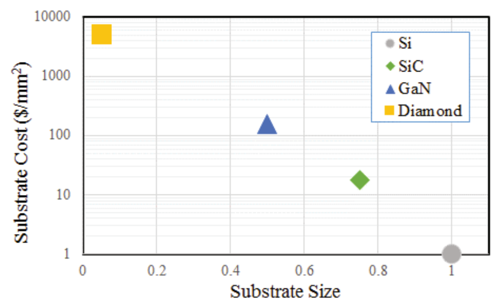

Fig. 2. Wafer cost per area for various WBG semiconductors versus available wafer size. The plot has been normalized to a 200 mm silicon wafer.

WBG semiconductors and devices are far less mature than their Si counterparts with limited availability; and have yet to be proven reliable in the field which further limits their adoption. Transistors have limited availability and manufacturer data sheets often do not specify important application-level reliability parameters such as the dV/dt rating, avalanche rating, and the safe-operating area, especially at elevated temperatures. The only commercial WBG power devices with more than 10 years of market performance are SiC Schottky diodes. As such, they are the only devices with proof of their reliability on the scale required for high-end applications. WBG devices cannot simply be swapped for Si devices in a circuit due to the dramatically different properties of the devices. Circuit designers will have to redesign systems to account for the WBG devices. Gate-driving circuits for SiC and GaN are more complex than those required for Si devices due to the high switching speed and common-mode noise can be more of an issue for WBG circuit designs. This leads to a large design inertia or reluctance to change in the circuit designers. Systems with significantly superior price to performance need to be demonstrated to overcome this inertia. In order to “unlock” the enormous potential of WBG power electronics and promote widespread adoption, devices need to be fabricated cost effectively to improve the device price to performance ratio and confidence in the reliability of WBG power devices in actual power electronics is needed. Failure mechanisms of WBG devices need to be understood and a fundamental understanding needs to be developed that links the basic material properties of commercially available WBG semiconductors to the reliability characteristics of power devices in power electronics. Systems need to be designed and demonstrated that take full advantage of the superior performance of the WBG devices to provide evidence that more efficient, lighter, smaller, and higher temperature capable power electronics than those made from conventional semiconductor materials can be cost effectively fabricated.

V. Overcoming the Barriers to Adoption

The U.S. Department of Energy's Advanced Research Project Agency - Energy (ARPA-E) has invested in WBG semiconductors to enable a new generation of power semiconductor devices that far exceed the performance of silicon-based devices. From materials and devices to modules and circuits to application-ready systems integration, ARPA-E projects have demonstrated the potential of WBG semiconductors to lower the cost of high-efficiency power electronics to enable broad adoption in energy applications [20].

In 2010, the ADEPT (Agile Delivery of Electric Power Technology) program [21] set out to improve the performance of power converters and power management systems using WBG semiconductors. The program sought innovations across the entire value chain from advanced component technologies and converter architectures, to packaging and manufacturing processes. Two projects investigating the potential of GaN devices were able to make tremendous advancements in their ADEPT projects. Transphorm's project "High Performance GaN HEMT modules for Agile Power Electronics" aimed to develop kW class inverters with greater efficiency and power density than incumbent Silicon based Insulated Gate Bipolar Transistor (IGBT) motor drives. The team overcame material challenges associated with the epitaxial growth of GaN on 6-inch Si with low defect densities in order to fabricate GaN-on-Si High Electron Mobility Transistors (HEMTs) which demonstrated improved power module performance over the state of the art Si IGBTs. A 600V normally-on HEMTs was developed by integrating a Si FET in a cascode configuration to achieve Enhancement mode operation [22]. Under resistive load switching, an inverter using the 600V GaN e-mode HEMTs hard switched at 100 kHz PWM frequency demonstrated an efficiency of 98.5%. When evaluated in a motor drive test lab side to side with a Si IGBT-based motor-drive inverter operating at 15 kHz PWM frequency, the GaN inverter showed 8, 4, and 2% improvement in efficiency at low, mid, and full loads (500, 1000, and 1500 W) operating at 7x higher PWM frequency [23]. In 2015, Transphorm, Inc. announced that its 600V GaN transistor had been JEDEC qualified [24]. Another ADEPT project, led by the Massachusetts Institute of Technology, took a broader approach and addressed three areas needed to improve power conversion: switching devices, inductors, and circuit design in their work focused on power converters for driving light emitting diode (LED) loads. In the device arena, MIT pioneered a tri-gate normally-off metal insulator semiconductor field effect transistor (MISFET) and demonstrated it with a breakdown voltage of 565 V at a drain leakage current of 0.6 μA/mm [25]. In parallel, MIT also developed a novel circuit that leveraged wide-bandgap power electronics. A 100 V input DC-DC LED driver that outputs 41 W with 94% efficiency and 24.8 W/cm^3 box power density was demonstrated. In addition, an LED driver for single-phase AC grid interfaces was developed operating from 120 VAC, while supplying a 35 V, 30 W output. The converter has a power factor of 0.89 with an overall box power density of 3.1 W/cm^3, operating at a variable switching frequency of 3-30 MHz with an efficiency of >93%. For comparison, commercial LED drivers typically operate in the 50-100 kHz frequency range, with maximum efficiencies around 85% and power densities <0.3 W/cm^3. The circuit design concepts developed during ADEPT resulted in the design of a new laptop charger now being commercialized by FINsix, a MIT spin-out. The charger (termed DART) is a 65 W charger that is 3 times smaller and lighter than conventional chargers.

The ADEPT program demonstrated the advantages of GaN based power electronics, however, it also exposed one of the barriers to widespread adoption: cost. Analysis of market drivers showed that widespread adoption would require driving down the costs of the components, which led to the creation of the SWITCHES (Strategies for Wide Bandgap, Inexpensive Transistors for Controlling High-Efficiency Systems) program [21] in 2014. The SWITCHES program was aimed at the key materials and device fabrication, and architecture issues that drive costs for WBG devices. The goal was to enable the development of high voltage (>1200 V), high current (100 A) single die WBG power semiconductor devices that would have the potential to reach functional cost parity with Si power transistors while also offering breakthrough relative circuit performance. The SWITCHES technologies would reduce the barriers to ubiquitous deployment of low-loss WBG power semiconductor devices in many cost sensitive applications.

One of the main drivers for the cost of WBG devices are the high cost of the substrates. In the case of GaN, wafers are expensive, limited in size & availability, and have a quality that depends on the fabrication method. Bulk GaN produced by the hydride vapor phase epitaxy (HVPE) method can provide substrates with diameters of up to 100 mm, but crystallographic quality and orientation is variable across the substrate. The ammonothermal crystal growth method, adapted from the hydrothermal method used to grow quartz crystals, produces higher quality GaN substrates but diameters are limited to 2-inch. Several projects under the SWITCHES program investigated reducing the cost and increasing the size of GaN substrates produced by the ammonothermal method. Soraa developed, in their SWITCHES and OPEN 2009 projects, a large diameter ammonothermal reactor capable of more than 600ºC operation and a pressure greater than 3,000 atmospheres in order to grow bulk GaN crystals. Soraa successfully demonstrated growth of GaN crystals that are over two inches in diameter at a rate of at least 10 microns per hour, and the fabrication of 2-inch GaN wafers from the crystals [26]. The wafers met Soraa's target specifications for LED crystal quality, dopant levels, dislocation density, miscut, and surface roughness. Soraa has also shown that with additional processing steps, they have the ability to make wafers with a dislocation density <1x10^4 cm^{-2}, a breakthrough that will enable higher-performing power electronics devices with a breakdown field greater than 3 MV/cm for GaN.

Potential pathways toward low cost GaN devices was investigated under the SWITCHES program. Two projects (Avogy, Inc. and Cornell University) were able to demonstrate near theoretical, high-power vertical GaN p-n diodes exhibiting breakdown voltages >4 kV and figures-of-merit (V_{BR}^2/R_{ON}) greater than 3 GW/cm^2 [27]. It was shown that vertical GaN devices were avalanche capable [28] indicating the ruggedness of such devices in breakdown, a critical requirement for power switching and rectifying applications. The projects demonstrated 80% process yield for the large area p-n junctions indicating the pathway towards ¢10/A for GaN devices is promising. With the current cost of 100 mm GaN wafers and a die size of 12-16 mm^2 for a 100A, 1200V device, vertical GaN devices should be capable of reaching the cost range of < ¢10/A.

Before the SWITCHES program, the majority of GaN power device development had been directed toward lateral architectures. There were simply no vertical GaN devices available. The lateral devices suffered from well-known issues such as current-collapse, dynamic on-resistance, inability to support avalanche breakdown [29] and usable breakdown voltages no greater than 650V. Vertical devices on the other hand have the possibility to realize the material-limited potential of GaN including true avalanche-limited breakdown. Tackling the device design and fabrication barrier the SWITCHES program created a new field of vertical GaN device designs to exploit the properties of the WBG semiconductor. Under the SWITCHES program the University of California, Santa Barbara demonstrated a modified vertical trench MOSFET, named OG-FET, which takes advantage of a regrown unintentionally doped GaN interlayer followed by an in-situ dielectric deposited in the trench for enhanced electron mobility. For a single unit cell OG-FET, V_{BR} as high as 700 V corresponding to a breakdown electric field of 1.4 MV/cm was reported with $R_{on,sp}$ of 0.98 mΩ-cm^2 [30]. Columbia University and MIT demonstrated a vertical fin power field-effect-transistor structure (VFET) on bulk GaN substrates. The VFET consists of fin-shaped channels etched into an 8-µm-thick n-doped GaN drift layer surrounded by metal gate pads which pinch-off the channel. Fabricated VFETs demonstrated threshold voltage of 1V, 10^{11} on/off current ratio, and a blocking voltage of 800V [31]. Vertical trench MOSFETs were demonstrated by HRL using an AlN/SiN dielectric stack employed as the gate "oxide" yielding a device with a threshold voltage of 4.8 V, blocking voltage of 600 V at gate bias of 0 V, and on-resistance of 1.7 Ω at gate bias of 10 V [32]. Avogy demonstrated 2.5A vertical transistors using buried p-layers and a hexagonal layout with breakdown voltages exceeding 1.5-kV and specific on resistance of 2.2 mΩ-cm^2 [33]. Reliability of vertical GaN devices is an area of interest with some preliminary initial investigations [34]. However, similar to other WBG semiconductors more work is needed to understand the degradation mechanisms in the material and in-field reliability demonstrations are still lacking.

A barrier in GaN device fabrication experienced by many SWITCHES project teams was the lack of a selective area p-type doping process in GaN. To confront this barrier the PNDIODES (Power Nitride Doping Innovation Offers Devices Enabling SWITCHES) program[21] was launched in 2017. The most obvious selective area p-type doping approaches, ion implantation and diffusion, have not produced p-type regions or satisfactory p-n junctions in GaN. Seven projects were selected for funding as part of the PNDIODES program. Three of the projects are focusing on ion implantation of p-type dopants along with innovative annealing processes to remove the implantation damage and activate the dopants. The innovative annealing processes, including laser spike and Gyrotron annealing, are needed to overcome the thermodynamic limits of GaN decomposition at high temperatures. Three of the projects are focusing on a non-traditional selective area doping process using patterned etch and regrowth to form selective p-type regions. These projects are developing low damage etching methods, interface impurity control, and optimization of regrowth on the different crystal directions to produce defect free regrowth interfaces. The remaining project is focusing on the development of neutron transmutation doping to fabricate a uniformly doped n-type GaN wafer by exposing the wafers to neutron irradiation to create a stable network of Ge dopants.

The CIRCUITS (Creating Innovative and Reliable Circuits Using Inventive Topologies and Semiconductors) program [21] was launched in 2017 to surmount the systems integration barrier. Previous efforts by ARPA-E and others have primarily focused on WBG material and device development without consideration of the circuit topology. The circuit design is also critical to the large-scale implementation of more efficient WBG devices as a result of their ability to operate at higher voltage, higher frequency, and higher temperature. New circuit topologies and designs are needed that optimize the properties of the WBG semiconductor devices in the circuit while minimizing the size and costs of auxiliary circuit components such as cooling systems. The CIRCUITS program seeks to accelerate the development of a whole new class of efficient, lightweight, and reliable power converters based on WBG semiconductors. With an explicit focus on novel circuit topologies, advanced control and drive electronics, and innovative packaging, CIRCUITS aims to catalyze disruptive improvements for power electronics afforded by WBG semiconductors. Twenty-one projects were selected for funding as part of the CIRCUITS program. The CIRCUITS project teams will develop efficient, lightweight, and reliable power converters for various applications including motor drives, automotive, power supplies, data centers, aerospace, distributed energy, and the grid. The circuit topologies employed by the CIRCUITS teams will be optimized for WBG semiconductors to maximize overall electrical system performance and offer significant direct and indirect energy savings. The CIRCUITS projects will establish the building blocks for WBG enabled power converters with higher efficiency, enhanced reliability, and superior total cost of ownership. In addition, a reduced form factor will drive adoption of higher performance and more efficient power converters relative to today's state-of-the-art systems.

Lastly, electricity provided via alternating current (AC) dominates today's power grid, from generation through distribution, to the consumer. DC power, however, brings a strong set of attributes for today's evolving grid, including lower distribution losses and higher power carrying capacity. DC distribution also facilitates the interconnection between battery storage and solar photovoltaic farms, which both operate naturally under DC. On the consumption side, over 50% of electricity used in the United States today arrives as DC at its point of use [1]. Combined with recent advances in wide band-gap semiconductors, voltage source converters, and DC-to-DC converters, there is a significant opportunity to enable greater use of DC in the distribution of electricity. The lingering risk of electrical fault scenarios (e.g., shorts and overloads) remains a primary hurdle preventing the growth of DC markets. In AC networks, electricity alternates direction periodically, naturally providing a "zero crossing" where no current flows for a brief moment, which allows electrical faults to easily be extinguished.

DC networks, on the other hand, deliver power without zero crossings, which greatly increases the likelihood of electrical arcs in conventional circuit breakers, making them useless in fault scenarios. There remains a significant technology gap in the safety and protection mechanisms required to mitigate potentially damaging faults in these systems. The projects that comprise ARPA-E's BREAKERS [21] (Building Reliable Electronics to Achieve Kilovolt Effective Ratings Safely) program will develop novel technologies for medium voltage direct current (MVDC) circuit breakers, applicable to markets including electrified transportation, MVDC (1-100 kV) grid distribution, renewable interconnections, and offshore oil, gas, and wind production. Project teams will either develop transformational improvements to conventional direct current (DC) circuit breakers (i.e., mechanical, solid state, hybrid) or construct circuit breakers based on completely novel designs. These systems must achieve program goals of handling a medium voltage between 1 – 100 kV DC and power above 1 MW at extremely high efficiencies and fast response times. Ultimately, innovations in MVDC circuit breakers could enable significant efficiency and resiliency improvements in the United States, transforming how electricity is delivered and managed across the entire power grid from generation to the end user.

VI. SUMMARY

Even with the considerable materials advantages, a number of challenges are preventing widespread adoption of power electronics using WBG semiconductors. Significant work still remains to overcome these barriers and realize the full potential of WBG materials in power systems including fundamental research into material properties and processing as well as continued development down the power electronics value chain into circuits and systems.

VII. ACKNOWLEDGEMENTS

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